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# GROUND WATER MODELLING WITHIN AN INTEGRATED WATER RESOURCES MANAGEMENT

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## ABSTRACT

The ground water resource is an important aspect in an integrated water resources management (IWRM). This contribution describes the application of a ground water model and its embedding into an IRWM in Darkhan region, Mongolia. The integration to the other aspects of water resources is also shown. To develop a sustainable IWRM strategy considering all water sectors GEO4 scenarios are selected and adopted to the model region. Especially for the ground water system the present and future water demand and the water abstraction by the local water supply company are taken into account. After implementation, data acquisition by level loggers, and model calibration, simulation results of the ground water model are presented.

***Index Terms –*** Ground Water, Integrated Water Resources Management, Scenario Development, Modelling, Simulation

## 1. INTRODUCTION

In many regions ground water resources are limited and in danger of pollution, but they are also the only source for clean drinking water. Faced with this, management strategies are necessary to deal with valuable rare ground water resources. Ground water models are used to evaluate resources and calculate management plans. But the ground water is connected to other environmental systems and thus a global view has to be taken in to account by modelling the ground water system within an integrated water resources management (IWRM).

The interdisciplinary approach to IWRM will be presented for the practical implementation of a ground water system within an IWRM for an arid region in Central Asia, where the BMBF research project "Integrated Water Resources Management in Central Asia – Model Region Mongolia" was realized. The methods of data acquisition, preparation, modelling, and simulation within the IWRM are illustrated and results presented.

## 2. GROUND WATER MODELLING

### 2.1. Ground Water Flow Equation

The ground water flow of a region can be modeled by the combination of the Darcy equation describing the connection between the porous media and the hydraulic gradient (grad *h*) and the continuity equation describing the change of stored water in relation to the change of hydraulic head *h*. The combination of both equations leads to the ground water flow equation, describing the water flow in porous media. It is a second-order partial differential equation (PDE) of the parabolic type:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y \frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_z \frac{\partial h}{\partial z}\right) = S\frac{\partial h}{\partial t}-q(x,y,z,t)$$

The hydro-geological conditions are expressed by the conductivity $k$ and the storage coefficient $S$. The left hand side of the equation describes the change of hydraulic head in three dimensions of space ($x$, $y$, $z$), the right hand side the change of stored water in aquifer over time and the inflow or outflow of water to the aquifer as a function of space and time determined by $q$.

### 2.2. Numerical Simulation

Depending on the complexity and hydro-geological conditions of the ground water problem different solution algorithms to solve the equation system can be used. Within the MoMo project the transient ground water flow was considered which results in a parabolic PDE for which boundary as well as initial conditions for ground water head are needed. Standard methods for the solution of such complex ground water systems are the finite element method (FEM) and the finite difference method (FDM).

Based on the hydro-geological conditions in the model area a partial differential equation for the description of the ground water system was derived. For simulation and optimization of the ground water system, the PDE has to be discretized in space, resulting in a large scale system of ordinary differential equations with a high number of state, input and output variables.

Within the MoMo project FDM was first used for this discretization [1]. In addition a new method, collocation on finite elements, was used for space discretization, which leads to a higher numerical accuracy in comparison to FDM [2].

### 2.3. Implementation of the Ground Water Model

Within the MoMo project the software Visual MODFLOW [3] was used to implement and simulate the ground water system. The software is based on the ground water tool MODFLOW developed by the U.S. Geological Survey (USGS). First the model area of Darkhan was defined and the corresponding PDE was discretized in space, which determines the structure of the ground water model.

The parameterization was done by assigning the prepared data to the ground water model. Hydrogeological parameters are allocated to the space-discretized model area. The parameters for infiltration, ground water inflow or outflow and measured ground water heads were defined as boundary conditions in different time scales. The locations of the wells were used and the pumping schedules provided. Finally the ground water model was calibrated based on the measured ground water level from the observation wells. Based on the calibrated model investigations to system behaviors were carried out by changing inputs to the ground water system.

## 3. INTEGRATED WATER RESOUCES MANAGEMENT

### 3.1. Integrated Water Resources Management

The ground water system stands in direct relation to the environment (Figure 1). To reflect this, the system is integrated in a larger IWRM model consisting of different interconnected detailed sub-models for different ecological and technical subsystems of the IWRM cycle [4].

The major inputs to the ground water system are the infiltration as a function of precipitation from hydrology, surface water levels as well as the morphology derived from river ecology investigations. The water quality, which is influenced by land use, nutrient cycling as well as river ecology, is also important. The main output of the ground water system is the ground water level and the amount of water allowed to be abstracted by pumps for drinking water purposes. The water abstraction should have a low impact on the ground water system.

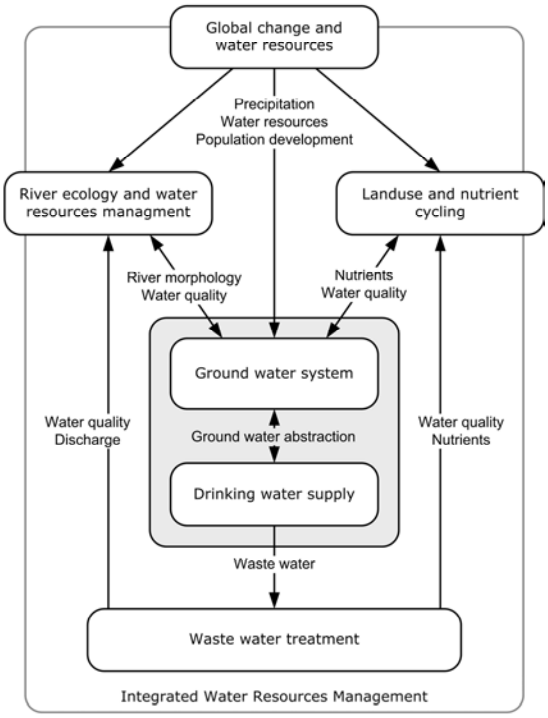


*Figure 1 Structure and interfaces of an IWRM*

### 3.2. Scenario Development

For simulation and model predictive analysis within the IWRM global scenarios were defined by the Global Environmental Outlook 4 (GEO4) [5].

This outlook is developed by a consortium of global experts and the UNEP, giving the development for several regions of the world. For the research project, the global scenarios for Central Asia were used and adapted for the model region Mongolia. Therefore the primary driver climate, economy, demography, and technical development were evaluated for their impact on the different subsystems of the IWRM and secondary drivers for each subsystem were derived. Related to ground water the drivers lead sub-scenarios for water availability, water use, and demand, which were used to simulate the ground water model within the IWRM.

The scenario approach of the IWRM concept was implemented to the ground water system considered. The climate scenarios as well as the GEO4 scenarios are important to predict the ground water situation. Climate scenarios were investigated in the sub-system of hydrology and applied to the local ground water system as boundary conditions which are uncontrollable inputs from infiltration and discharge. Within the climate scenario framework two global GEO4 scenarios were investigated, also providing inputs to the system. The “market first” and “sustainability first” scenarios were defined as research aims of the MoMo project.

### 3.3. Impacts to the Ground Water System

Impacts on the ground water system are mainly from the primary driver of the local economy and population development, leading to different scenarios in water use by agriculture, mining, industry and households. The ground water abstraction is directly influenced by the water demand from different sectors. Recharge of the ground water is influenced by precipitation depending on climate and related scenarios.

According to the given scenarios the boundary conditions and the inputs to the ground water system were defined and used for simulation to reveal potential problems of actual and future situations. The remaining degree of freedom is the ground water abstraction. This was used to derive optimal sustainable ground water abstraction strategies.

## 4. IMPLEMENTATION OF THE GROUND WATER MODEL

### 4.1. Model Area

The model region of the IWRM considered in this study is the catchment area of the Kharaa River in northern Mongolia. The main focus of the investigation for the ground water system is on the lower catchment area of the Kharaa River, especially the ground water system near the city of Darkhan. The flow of ground water mainly occurs in a band along the river which determines the ground water system. The level of the ground water is dependent on the season, in average around 3m below the ground.

The unconfined ground water aquifer is characterized by alluvial sand and gravel with interlaced sandy loam [7][9]. Due to the porous media the conductivity of the aquifer is high, mainly 10 to 100 m/day, partly up to 300m/day. The main water bearing stratum extends with a width of 10 to 20 km along the Kharaa River, reaches a thickness of 70 m near Darkhan, and is divided up into different layers. The ground water recharge from precipitation is very low in the Darkhan area. The recharge depends on the inflow of ground water from aquifers of the upper catchment area where the precipitation and ground water infiltration are much higher.

In the upper reaches of the Kharaa River the ground water is mainly extracted from mining activities mostly situated in this area. The ground water for drinking water consumption is abstracted in small villages along the Kharaa River, but the largest influence on the ground water is caused by the drinking water abstraction for the Darkhan city where drinking water is extracted by local water companies. The drinking and waste water company USAG Darkhan extracts around 20,000 m$^3$/d water from 18 wells, and the thermal power plant of Darkhan extracts 5,000 m$^3$/d for hot water production and further 3,000 m$^3$/d as process water for the thermal process. Additional 8 wells are located in the industry area of Darkhan with unknown ground water extraction. Furthermore there are a lot of small private wells with a negligible amount of water abstraction.

### 4.2. Data Acquisition and Basis

*4.2.1. Hydro-geological and Climate Data*

To establish a ground water model spatial data like topographical maps and elevation data, e.g. SRTM data, were used to set up the physical boundaries of the model area. For determining the model parameters hydro-geological data such as cross-sections and well passports of USAG wells as well as hydro-geological maps were used [7]-[9]. These data were assembled and prepared using a GIS system.

Climate data in the form of temperature, precipitation, infiltration as well as river morphology or water level of the river were used to set up boundary conditions of the model. In addition, ground water extraction and location of abstraction wells were necessary due to the fact that they have the most important man-made impact on the ground water system. Four data logger were installed to achieve measurements of ground water level, because there were no measurements in the past. All these time series data were assembled and analyzed using MATLAB® [6]. Since these data provide inputs or boundary conditions for the simulation model, they can be utilized to generate input data vectors, e.g. for different ground water scenarios.

*4.2.2. Monitoring of Ground Water Level*

For ground water modelling and model calibration it is necessary to measure the ground water level. The location of observation wells should be determined, so that as much as possible information on the ground water level can be achieved. However the hydro-geological conditions of the catchment area have to be taken into account. Since there was no observation by Mongolian institutions or water suppliers in Darkhan we established a new pilot monitoring system by installing data loggers in unused local abstraction wells. Here automatic data loggers were used for a continuous measurement of the ground water level. The measured data were modified with the air pressure compensation and the sea level conversion.

For investigations in ground water abstraction a well passport was designed to gather information about the observation wells such as the location, usage, filter system, pumped water amount, etc.

*4.2.3. Ground Water Extraction*

The data of ground water extraction were collected and digitized within the project. For abstractions from USAG from 2003 to 2009 and from the power plant from 2007 to 2008 are available. However, information about the ground water extraction from the industry is not available and must be collected in further work. For ground water modelling, the data were automatically processed by the computer programs developed.

The total ground water abstraction from USAG is given in Figure 2, showing a seasonal changing abstraction, reaching the maximum in the winter. A trend for decreasing water abstraction can be recognized. The water use of the Darkhan city has not changed in the last years. Thus this decreasing ground water abstraction may be caused by companies and institutions installing their own wells for water abstraction, like most companies in the industrial area as well as the power plant. This lowers the ground water abstraction from wells of USAG, but does not lower the total ground water abstraction in this region at all.

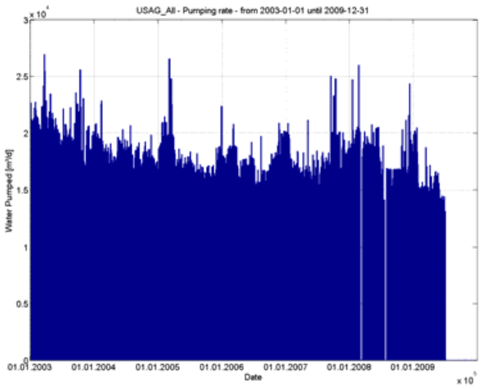


*Figure 2 Ground water abstraction of USAG*

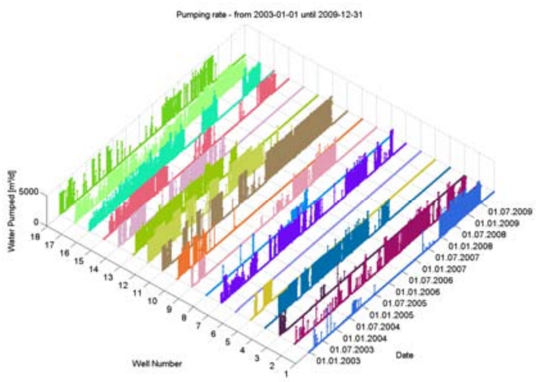


*Figure 3 Ground water pumping strategies of USAG*

The pumping schedules of USAG are given in Figure 3. In the past nearly all wells were used for ground water abstraction. Having a look at the year of 2009 only a few wells were used. This is due to the fact that not all wells are equipped with pumps. Despite of these facts, enough ground water is abstracted to satisfy the drinking water demand.

### 4.3. Model Implementation

Based on the acquired data a ground water model for the area of Darkhan was established in cooperation with the hydro-geological scientists of the Mongolian University of Science and Technology (MUST) Ulaanbaatar. We developed a detailed model for the region around the USAG wells. A further model containing wells of USAG and power plant was established from MUST Ulaanbaatar and TU Ilmenau together.

The ground water model was established using the software Visual MODFLOW. For further investigations MATLAB was used to transfer the ground water model to a state space model based on the data from the MODFLOW model.

Initial hydro-geological parameters were abstracted from maps, well passports and cross sections. Then the model calibration was carried out using the measurement data of the ground water level. Now the model is capable of describing the current situation and predicting future trends of the ground water system. This model will also be used for investigating the scenarios within the IWRM and the calculation of sustainable water abstraction strategies based on optimization methods.

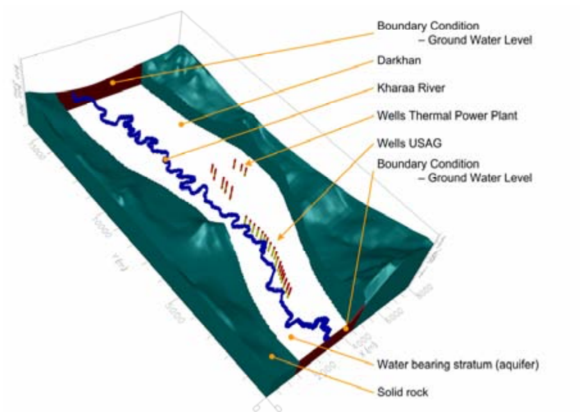


*Figure 4 Ground water model for region Darkhan*

The first model (Figure 4) was defined for the area of Darkhan because this is the largest area influencing the ground water system in the sub-catchment of the Kharaa River and therefore is most important for the development of water abstraction strategies. During the project the significant impact of mining was not investigated. Thus further investigations should take this into account.

### 4.4. Model Calibration

Within the project data loggers were installed in the wells of USAG and the thermal power plant to monitor the ground water level. The measurement results were read out monthly and used for model calibration. The data loggers will be left in these wells and maintained by local staff in cooperation with the water authority of the Darkhan city. Measurement results of ground water level for observation wells at USAG are shown in Fig. 5.

They indicate a significant seasonal change. The lowest water level was reached at the end of the winter, due to the low ground water recharge caused by the low precipitation and the accumulation of water in snow. A high water level can be seen at the beginning of the summer in correlation to the high water level of the Kharaa River. The measurement values will be used for model calibration and reference trajectories for the optimization of the ground water system. Measurement values of the thermal power plant can not be used because the data logger installed in the pumping well does not reflect seasonal change of the ground water level.

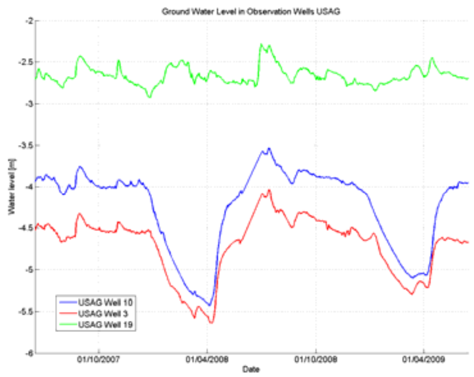


*Figure 5 Ground water level in observation wells*

## 5. SIMULATION RESULTS

Simulation results are shown in Fig. 6. The impact of ground water abstraction can be seen from the decrease of ground water level at the wells of USAG and the power plant. The significant decrease of ground water level at USAG occurs due to a specific pumping schedule, i.e. 5 pumping wells working at the same location at the same time. The ground water level came back to the normal value, when pumping activities were switched to other pumps. Depending on the pumping strategies different impacts to ground water level can be found. A permanent sink of the ground water level could be seen at the wells of the power plant, corresponding to the measured ground water level caused by permanent pumping of all 8 wells. Nevertheless, at present there is no problem with the ground water quantity in the considered area because the ground water recharge is still enough.

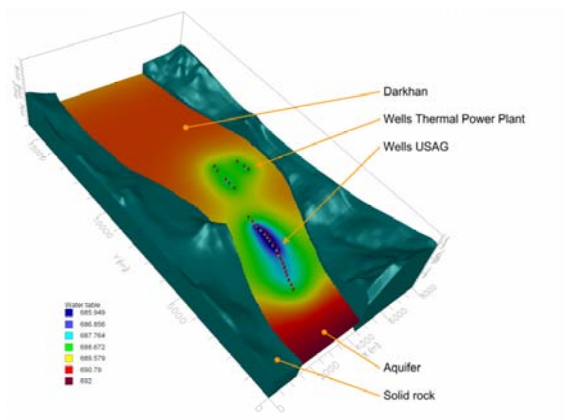


*Figure 6 Simulation results for the region Darkhan*

## 6. CONCLUSIONS

The paper has shown the modeling and simulation of a ground water system. The subject of investigation was a ground water system in Darkhan region, Mongolia. The simulation results presented within an integrated water resources management framework show the influences from and to other sectors of water resources. The model serves as the base for future study of sustainable ground water management strategies within the IWRM framework.

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## 7. REFERENCES

[1] Anderson, M. P. and W. W. Woessner. "Applied ground water modeling: simulation of flow and advective transport", Acad. Press, San Diego, 1994.

[2] Villadsen, J., and M. L. Michelsen, Solution of differential equation models by polynomial approximation, Englewood Cliffs, Prentice-Hall, NJ, 1978.

[3] Schlumberger Water Services, "Visual MODFLOW", Schlumberger Water Services, 2009.

[4] Global Water Partnership, "A Handbook for Integrated Water Resources Management in Basins", Global Water Partnership and the International Network of Basin Organizations, Eleanders, Sweden, 2009.

[5] United Nations Environment Programme (UNEP), "Global Environmental Outlook - GEO4", Progress Press Ltd, Malta, 2007.

[6] The MathWorks Inc, MATLAB®, The MathWorks Inc., 2009.

[7] Batsukh, "Hydrogeological Report for Darkhan", Mongolian University of Science and Technology, School of Geology and Petroleum Engineering Ulaanbaatar, 2007.

[8] Jadambaa, N., "Mongolyn gidrogeologijn zurag = Hydrogeological map of Mongolia", GEBH, Ulaanbaatar, 1996.

[9] Jadambaa, N. and W. Grimmelmann, "Hydrogeological map of Mongolia 1:1,000,000 : explanatory notes", Schweizerbart, Stuttgart, 2003.